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EFFECT OF MANUFACTURING ERRORS ON FIELD QUALITY OF DIPOLE MAGNETS FOR THE SSC*

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Abstract

For superconducting dipole magnets of the sort proposed for the Superconducting Super Collider, the effects of various random manufacturing errors upon random magnet-to-magnet magnetic-field aberrations are analyzed. The errors considered are ones that are directly related to manufacturing tolerances and measurable dimensions of parts and materials. These errors affect the position of the boundaries of each layer of conductors in each quadrant and the positions of conductors within those boundaries.

Manufacturing errors were estimated for the Fermilab Tevatron magnets and the BNL CBA magnets. The estimates were then adjusted so that the calculated field aberrations matched the measured values. Those errors were then applied to the SSC magnet reference designs currently under study in order to obtain estimated field aberrations.

The Problem

A vital factor in the design of the Superconducting Super Collider (SSC) is the estimation of random magnet-to-magnet field aberrations resulting from random manufacturing dimensional errors. These aberrations will affect the paths of the circulating particles, which in turn will determine whether the proposed magnet designs will function adequately. The estimation of these field aberrations was the primary purpose of this study.

The Approach to a Solution

The approach used in this study was to: identify a set of mechanical error modes that are directly associated with manufacturing tolerances and measurable dimensions of components; calculate the field aberrations resulting from unit manfacturing error for each mode; estimate the magnitude of the error for each error mode; and finally, fold the latter two together into an estimate of expected field aberrations.

Two large groups of magnets have been constructed: those for the Colliding Beam Accelerator (CBA) and the Tevatron. While few dimensional error data are readily available, extensive field aberration data are at hand, and so this approach was made using the data from those magnets. It was assumed that the errors for the SSC designs would be similar but scaled according to the size of the magnet cross sections.

The Magnets

The cross section of a typical magnet is shown in Fig. 1. The primary dimensions of the magnets under consideration are listed in Table 1 together with ratios of some of the dimensions. The ratios illustrate that the magnets are by no means geometrically similar, and so the various manufacturing errors affect the field aberrations for each magnet design differently.

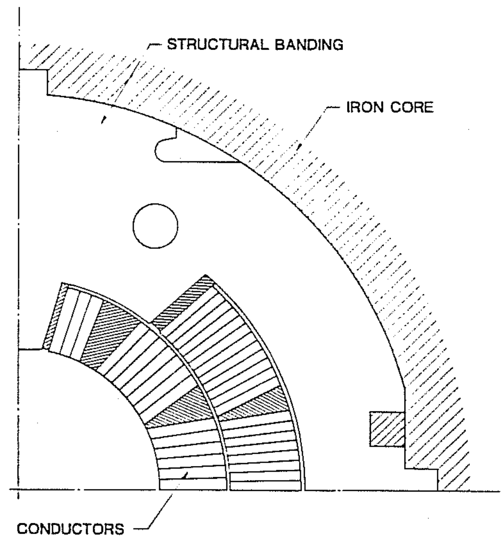

Fig. 1. Typical magnet cross section; SSC Design D. First quadrant shown.

Table 1. Magnet Dimensions

Dimensions are in centimeters.

	Radii Coil inside a_1	Radii Coil outside a_2	Radii Iron inside b	Ratios a_2/a_1	Ratios $b/\bar{a}$
CBA	6.547	8.200	8.655	1.252	1.258
Tevatron	3.810	5.459	9.563	1.433	2.310
SSC Design A/D	1.999	3.993	5.570	1.997	2.323
SSC Design B	2.604	4.446	inf.	1.707	inf.
SSC Design D-5cm	2.499	4.493	6.070	1.798	2.095

$\bar{a} \doteq a_1 + 0.2(a_2-a_1)$

Mathematical Representation of The Coils

Most of the error modes can be expressed in terms of movements of one or more of the boundaries of the conductors in the two coil layers in the various quadrants. For the purpose of this study, the cross section of each of the two layers of the magnet coil was represented by a region bounded by circular arcs and radial lines in which the current density varies inversely with radius. This representation admits to a simple mathematical description of the magnetic field and its partial derivatives with respect to boundary positions. An additional mode, the turn-to-turn variation in conductor azimuthal width, was considered.

Manufacturing Error Modes

It was assumed that the field aberrations are dominated by errors in magnet cross section, and that the effects of variations of the shapes of the ends are small.

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between the measured and calculated multipoles. The normal dipole field variation was ignored in this procedure as it was felt that a major part of it resulted from variation in coil length. A reference radius of about 0.9 of the coil inside radius was used, instead of the usual 2/3, in order to emphasize the higher-order multipoles.

A similar procedure was applied to the Tevatron magnets, except that the measured errors were permitted to vary also. The resulting manufacturing errors are presented in Table 3, and the corresponding field aberrations in Table 4.

Table 3. Fitted Manufacturing Errors

(Units: milli-inches.)

Error mode group	Initial estimates for CBA (1)	Fitted errors CBA	Fitted errors Tevatron
1	2.0	0.95	1.77
2	2.5	0.45	0.07
3	2.0	6.55	4.54
4	2.7(2)	2.70(3)	0.16
5	1.4(2)	1.40(3)	0.04
6	1.0	0.10	0.61
7	2.0	0.20	0.06
8	2.5	0.28	0.07
9	3.0	0.17	0.09
10	0.1	0.014	0.30

(1) Estimates by Peter Wanderer, BNL.
(2) From coil measurements.
(3) Held fixed during fitting procedure.
Unit errors correspond to ε in Table 2.

Table 4. Measured and Calculated Field Aberrations for CBA and Tevatron Dipole Magnets

(Units: 1/10000 of the dipole field at a reference radius of 2/3 of the coil inside radius.)

CBA Dipole Magnets

n	Skew component, a Meas.	Calc.	Diff.	Normal component, b Meas.	Calc.	Diff.
0		2.156			3.676	
1	2.64	2.914	.274	.92	.874	-.046
2	.46	.609	.149	1.89	2.044	.154
3	.72	.576	-.144	.23	.206	-.024
4	.18	.099	-.082	1.16	.786	-.374
5	.121				.034	
6	.11	.049	-.061	.22	.296	.076

Rms of differences, .17

Tevatron Dipole Magnets

n	Skew component, a Meas	Calc.	Diff.	Normal component, b Meas.	Calc.	Diff.
0		4.31		4.63		
1	2.9	2.89	-.01	1.9	2.24	.34
2	1.2	1.18	-.02	2.5	2.44	-.07
3	1.5	.89	-.61	.8	.64	-.16
4	.5	.29	-.21	1.3	1.18	-.12
5	.6	.33	-.28	.3	.18	-.12

Rms of differences, .26
See text for nomenclature.

Using this procedure, one can obtain rather different sets of manufacturing errors that give calculated field aberrations that agree about equally well with the measured ones. When these errors are applied to the CBA designs, however, the resulting field aberrations are about the same. It must be emphasized that the listed errors are not necessarily the ones that exist, but are merely ones that <u>could</u> exist. They certainly are <u>not</u> to be interpreted as tolerances; that's a whole 'nuther ball game.

Application of Errors to SSC Magnets

Feeling that the manufacturing errors for the SSC magnets can and should be smaller because the magnets are smaller, we scaled the errors according to coil radius to the 0.3 power -- giving about a 20% reduction in errors for a coil half the size -- and used a radius to a point 1/5 of the coil thickness out from the inner radius.

The scaling factors, easily reproduced using the data in Table 1, range from a low of 0.729 for scaling from the CBA to Design A/D, to a high or 0.905 for scaling from the Tevatron to Design B.

The resulting field errors for each of the three SSC designs were then calculated using the errors for the CBA and Tevatron. Some of the calculated multipoles resulting from the matching procedure were smaller than the measured ones; for the SSC magnets, a factor representing the ratio of measured to calculated values was applied to those multipoles.

For each of the three SSC magnet designs we then had two rather different sets of estimated multipoles, one from the CBA and the other from the Tevatron magnets. Rather than average the results in some fashion, we conservatively adopted the larger value of each multipole. The results are shown in Table 5.

Table 5. Estimated Random Field Aberrations for the SSC Reference Design Magnets

(Units: 1/10000 of the dipole field at a reference radius of 10 mm)

n	Des. A/D a_n	Des. A/D b_n	Des. B a_n	Des. B b_n	Des. B-5cm a_n	Des. B-5cm b_n
0	5.2	5.7	5.1	6.1	4.8	5.2
1	3.2	1.7	2.9	1.7	2.4	1.3
2	.48	1.6	.44	1.15	.30	1.00
3	.54	.21	.34	.16	.27	.11
4	.11	.48	.059	.25	.048	.19
5	.083	.052	.022	.020	.028	.017
6	.026	.040	.0078	.016	.0051	.0106
7	.012	.0093	.0030	.0021	.0025	.0020
8	.0043	.0033	.0008	.0009	.0007	.0006
9	.0012	.0018	.0002	.0003	.0002	.0003
10	.0006	.0018	.0001	.0001	.0001	.0002
11	.0005	.0002	.0001	.0000	.0000	.0000

See text for nomenclature.

The estimated quadrupole (n = 1) components are probably intolerably large. In principle they can be reduced by shimming the position of the coil with respect to the iron following room-temperature measurements of the magnetic field, but at some expense.

Conclusions

The field aberrations presented in Table 5 are the current best estimates. Refinements might be made in the near future as time permits.